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A SYSTEMATIC APPROACH TO ANALYSE CRITICAL TRIBOLOGICAL PARAMETERS IN AN INDUSTRIAL CASE STUDY OF PROGRESSIVE DIE SEQUENCE PRODUCTION

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Summary

In a production line that uses sheet metal forming technology, the surface quality of the final part and tool life depend significantly on the lubricant performance. Hazardous chlorinated paraffin oils have been widely used by manufacturers throughout the world for many decades. However, with growing environmental awareness, the trend is to substitute environmentally hazardous oils with environmentally friendly lubricants. Tribological conditions in forming operations depend on several parameters such as process speed, workpiece/tool interface pressure, workpiece/tool interface temperature and surface roughness of the parts. Prior to testing several tribo-systems in the laboratory to determine the limit of lubrication, it is therefore important to identify the tribological parameters in the production process.

This paper describes a generic methodology for such an investigation to determine the tribologically critical parameters in an industrial production line in which a progressive tool sequence is used. The current industrial case is based on multistage deep drawing followed by an ironing operation. Severe reduction in the ironing stage leads to high interface temperature and pressure. As a result, subsequent lubricant film breakdown in the production line occurs. The methodology combines finite element simulations and experimental measurements to determine tribological parameters which will later be used in laboratory testing of possible tribology systems.

1. Introduction

Testing of new, environmentally friendly tribo-systems in production tools involves considerable costs and risks due to production stops and possible breakdown of the tool. A solution may be adapting a simulative test. For that, a tribotester has been designed and a methodology has been developed for off-line testing of various tribo-windows at the laboratory [1]. The tribotester has the ability to run multiple strokes giving the opportunity to emulate the process conditions close to the ones in the industrial production line. Furthermore, the equipment enables to mount different tools to emulate the desired production process [2, 3]. However, usability of the off-line test results highly depends on the accurate analysis of the production platform that affects the active lubrication mechanism during production. Liquid lubrication mechanisms in sheet metal forming are influenced by a number of parameters including tool and workpiece geometry and surface topography, lubricant bulk modulus and viscosity which is influenced by tool-workpiece interface

pressure, temperature and sliding speed. It is therefore important to analyse the production process accurately, and then determine the tribological parameters of the given production process and perform the laboratory testing accordingly.

This paper presents a systematic approach on how to analyse a given production process of a progressive die sequence before off-line testing. Combined finite element analysis and experimental measurements are used to determine tool-workpiece interface pressure and temperature of the critical station, whereas other tribologically important parameters such as sliding speed, sliding length and tool roughness are defined. These identified parameters will later be used in off-line testing of various tribo-windows.

2. Case Study

For this study, an industrial production line at the Danish company Grundfos A/S was chosen. The selected production line concerns the

manufacturing of a stainless steel bearing plate used for a water pump.

The 13 steps progressive tool sequence of the precision sleeve is given in **Fig. 1**. The main shape of the part is determined in the five stages marked on the figure. The sheet metal forming operations taking place in these stations are 1- deep drawing, 2- reverse drawing 3- redrawing 4- punching 5- collar drawing and ironing. The stations between 3 and 4 are either blank stations or the deformation takes place only along the flange and therefore not taken into account in this study.

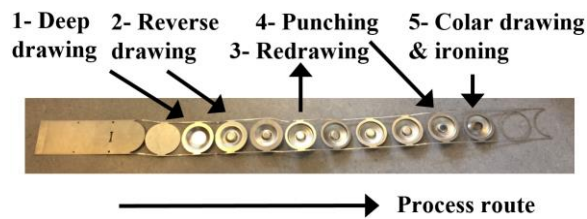


Figure 1. Illustration of the bearing plate production in progressive tool sequence.

The critical operation in this specific production platform is number 5, the combined collar drawing and ironing. Due to severe contact conditions, i.e. high tool-workpiece interface pressure and temperature, the lubricant film is thinned. Unless very efficient boundary lubricants are applied, the lubricant film breaks down, which results in workpiece metal pick-up on the punch stem and scoring of subsequent workpiece surfaces. Before proceeding with off-line testing in the laboratory, it is essential to calculate the tribologically wise most influential parameters in the production case.

3. Determination of Tribo-parameters

3.1 Process parameters

The workpiece is an austenitic stainless steel strip EN 1.4301 with 50 mm width and 1.5 mm thickness. During ironing the wall thickness of the plate is reduced to 1 mm and the ironed wall length is 10 mm. The punch and lower die material at the ironing station is powder metallurgical cold work tool steel VANADIS 4E, with hardness 61 HRC. The ironing punch is coated with AlCrN and the roughness of the punch nose is $R_a=0.06$. The lubricant used in the ironing station is LA 722086 with a kinematic viscosity 900 cSt at 40 °C. The lubricant is applied through the channels in the punch. The industrial ironing operation uses a Raster 400 ton

mechanical press with link drive operating at 38 strokes per minute.

The two most important parameters process parameters governing lubrication are the normal pressure and the temperature in tool/workpiece interface.

3.2 Analysis of pressure distribution

The pressure distribution in the tool/workpiece interface in the critical station 4, collar drawing and ironing is determined by numerical simulation of the four sheet metal forming operations (1)-(4) in a 2D axisymmetric model using the elasto-plastic FE code LS-DYNA. The tools were modeled as elastic materials. The initial flow curve of the blank was determined by plain strain compression testing [4]. The displacement curve and the tooling geometry of each operation were provided by Grundfos A/S. After the first operation was completed, the information on the strain and stress were saved in a file and imported into the simulation of the subsequent station. The procedure was followed until operation (5), which includes the ironing.

The numerical model used for the ironing station is shown in **Fig. 2**. Discretization was performed until the pressure distribution was converged. The overall tooling system and the blank were discretized by approximately 5000 and 1250 elements, respectively.

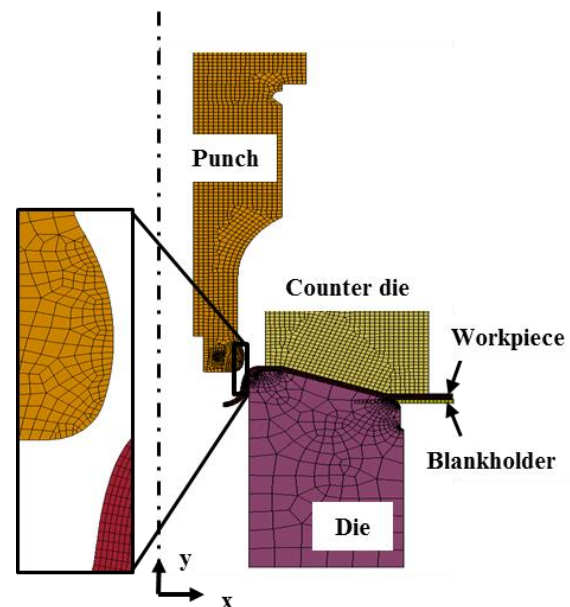


Figure 2. Numerical model used for the analysis of the ironing operation with the details of workpiece and punch node mesh.

Fig.3 shows the normal pressure in radial direction for a single stroke during ironing for both the forward stroke and the backward stroke.

The normal pressure on the punch nose is around 1050 MPa during forward stroke. During the backward stroke, the normal pressure reaches up to 2050 MPa. This is due to large strain hardening after the main wall reduction. Elastic contraction of the lower die results in additional reduction during ejection of the punch, and very small contact length between workpiece and die leads to large pressure gradients especially at the end of the backward stroke where the local blank thickness is relatively larger.

For the validation of the numerical model, the thickness and the part profile along the ironed zone were measured. Both measured and calculated wall thickness was found as 1.04 mm.

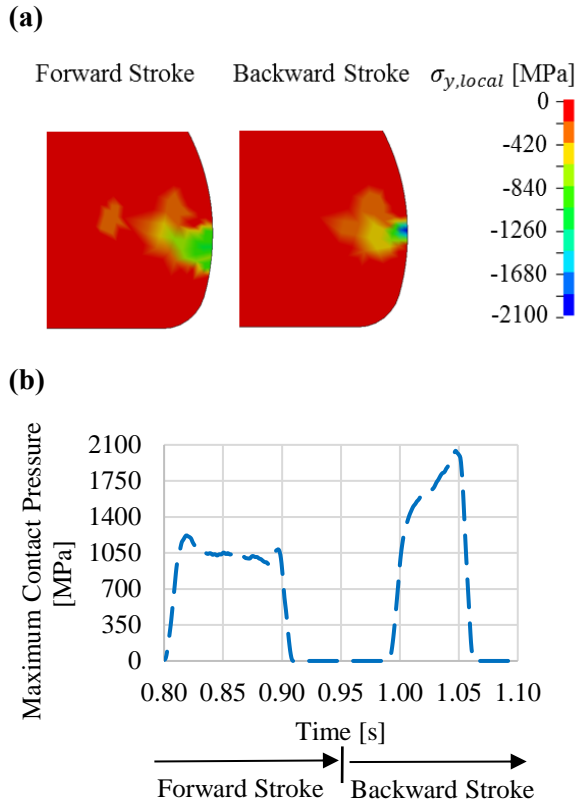


Figure 3. (a) Distribution of maximum contact pressure at the punch nose during forward and backward strokes and (b) Evolution of contact pressure with respect to time.

3.3 Analysis of temperature distribution

Analysis of the tool-workpiece interface temperature was performed in two steps: i) steady-state thermal analysis of the punch and ii) thermo-mechanical analysis of the ironing process.

The first step of the numerical analysis is to estimate the temperature distribution in the ironing punch when the steady-state condition is reached. The experimental measurements of temperature in a few points of the tool were given

as input for thermal modelling of steady-state. The calculated steady state temperature field is illustrated in **Fig. 4**. The aim of this model is to determine a temperature field for the punch without running multiple simulations before reaching steady state.

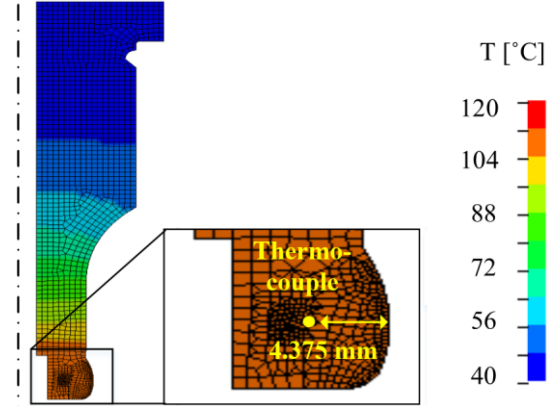


Figure 4. Temperature distribution within the punch after steady state analysis with the detail of thermocouple position

The second step of the numerical analysis of the ironing process is based on the thermo-mechanical coupled approach. The temperature distribution of the tool obtained in a previous step (See **Fig. 4**) was used as a boundary-condition in the subsequent thermo-mechanical analysis. This means that the heat losses and heat generation due to plastic and frictional work are calculated. Thus, the temperature dependency of the mechanical properties of the workpiece and the tool are taken into account.

Table 1. Material parameters used in numerical simulations.

Parameter	Tooling Vanadis4E	Workpiece 1.4301
Structural density [g/m ³]	7.7	7.9
Young's modulus [GPa]	206	200
Heat conductivity [W/mK]	30	15
Heat capacity [J/kg·K]	460	500
Heat convection with lubricant [W/m ² ·K]	150	-

The material properties were provided by the company and are presented in **Table 1**. The initial temperature of the strip before the ironing step was measured as 40°C and the lower die was

42°C. The heat transfer coefficients between the punch and the strip and between die and the strip were assumed as 100 kW/m²K [4]. In production, the lubrication for the ironing operation is provided both before and after the forward stroke and high amount of lubricant is flushed. The friction coefficient was therefore estimated as 0.04 [5].

To have a robust system, tools were assumed rigid when coupling thermal and mechanical solvers in LS-DYNA. In order to take into account the elastic expansion and deflection of the lower die, its radial displacement was measured from the model with elastic tools. The lower punch expands 0.03 mm during the forward stroke and 0.015 mm during the backward stroke. The displacements were implemented to the model that uses rigid tools. The calculated temperature is shown in **Fig. 5a** with dashed lines. The comparison of the calculated temperature and the temperature measured by a thermocouple shows a good fit.

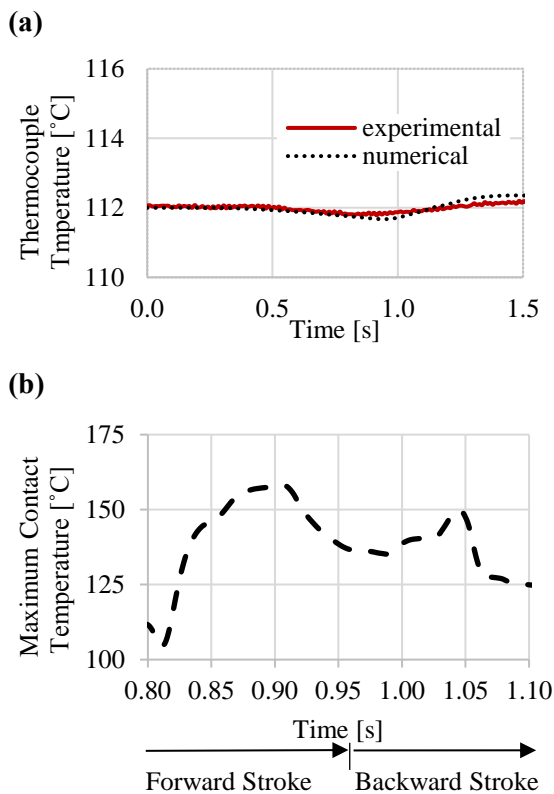


Figure 5. (a) Experimental and calculated temperature evolutions and (b) calculated maximum contact temperature.

Fig. 5b represents the maximum contact temperature along the tool-workpiece interface as a function of time for a single stroke. For the given ironing process, reduction during the forward stroke was 20 % and 4 % during the

backward stroke. Due to that, blank deformation contributes to the temperature rise at the contact both during forward and backward strokes. Furthermore, the backward stroke takes place at higher speed so that the same displacement occurs in shorter time. All in all, the instantaneous maximum temperature curves with both deformation and frictional heating reaches around 158 °C and 150 °C for forward and backward strokes, respectively.

5. Conclusions

The present paper describes a generic methodology to determine the tribologically critical parameters. The following was determined for the specific case study:

- The maximum tool-workpiece interface pressure is observed during the backward stroke of the punch and reaches 2050 MPa.
- The peak temperature in the tool-workpiece interface is approximately 158°C for the forward stroke and 150°C for the backward stroke.

The future work includes testing with recently developed tool [3] to emulate industrial ironing processes and suggestions to avoid the lubricant breakdown in production.

Acknowledgements

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